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Citation for published version:
Fernandez, MI, Go, YI, Fruh, W-G & Dennis Wong, ML 2025, 'Projection of Electricity Generation Profiles and Carbon Emissions Towards 2050: A Malaysia Context', *Energy for Sustainable Development*, vol. 85, 101681. https://doi.org/10.1016/j.esd.2025.101681

Digital Object Identifier (DOI):
10.1016/j.esd.2025.101681

Published In:
Energy for Sustainable Development

Energy for Sustainable Development 85 (2025) 101681

Contents lists available at ScienceDirect

Energy for Sustainable Development

journal homepage: www.journals.elsevier.com/energy-for-sustainable-development

Projection of Electricity Generation Profiles and Carbon Emissions Towards 2050: A Malaysia Context

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ARTICLE INFO

Keywords:
Energy system
Modelling
Climate change
Renewable
Storage
Optimisation

ABSTRACT

The planning of future energy systems that incorporate a significant share of renewable energy (RE) is gaining importance as a solution to energy security and environmental issues. In bottom-up energy system modelling, there are two primary approaches: one focuses on optimising the energy mix for a specific target year (static), while the other seeks to optimise the transition from the current reference to a target year (long-term). This paper aims to model and analyse Malaysia's renewable energy transition towards 2050 with both static and long-term approaches. The Low Emissions Analysis Platform (LEAP) was used to develop five Malaysian national energy system models from 2020 to 2050 with primary focus on the power sector. Optimal energy storage capacities were investigated in the National Energy Transition Roadmap (NETR 2050) model using the coupling of LEAP with Next Energy Modelling system for Optimization (NEMO). For the Reference Model (2020), the total electricity generation was at 153.8 TWh/year mainly driven by coal and natural gas. With LEAP-NEMO optimisation in the NETR 2050 model with the integration of battery energy storage systems (BESS) and pumped hydro storage (PHS), the total annual electricity generation was 270.6 TWh/year with contributions from natural gas and solar. For the total emissions in all sectors, the results for models 1 to 5 resulted in 287.5, 321.5, 382.1, 404.5, and 466.3 Mt. CO2 respectively. With LEAP-NEMO optimisation and energy efficiency for demand reduction, model 5 was improved to be at 449.7 Mt. CO2 mainly due to the smaller electricity generated by natural gas in the power sector. Based on the economic results of the two long-term scenarios, the total net present value was calculated to be 1210.7 billion USD for NETR 2050 with respect to Ref (2020). With the LEAP-NEMO optimisation, the total net present value resulted in 1005.7 billion USD. Based on the LEAP results, a significant shift in the technological landscape will be required, with RE, energy storage systems (ESS), and energy efficiency taking on key roles. The findings from this paper can aid researchers and policymakers in creating strategic plans in RE and ESS development that can be applied to the case of Malaysia and other countries.

Introduction

The global focus on renewable energy (RE) as a key future resource is increasing rapidly. Although solar energy currently contributes just 3.6 % to worldwide electricity production, it has made a notable impact within the RE sector. In 2022, solar energy accounted for almost 31 % of

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Abbreviations: ASEAN, Association of Southeast Asian Nations; BaU, Business as Usual; BESS, Battery Energy Storage Systems; CAGR, Compound Annual Growth Rate; CCUS, Carbon Capture, Utilisation, and Storage; CO2, Carbon Dioxide; ESS, Energy Storage System; FiT, Feed-in Tariff; GHG, Greenhouse Gas; GSO, Grid System Operator; IEA, International Energy Agency; IEEJ, Institute of Energy Economics, Japan; LEAP, Low Emissions Analysis Platform/Long-range Energy Alternatives Planning System; MARKAL, MARKet ALlocation; Model 1, Reference Model 2020; Model 2, MyRER BaU 2025; Model 3, MyRER NCT 2035; Model 4, NETR 2040; Model 5, NETR 2050/NETR 2050 OPT; MyRER, Malaysian Renewable Energy Roadmap; NCT, New Capacity Target; NEMO, Next Energy Modelling System for Optimization; NETR, National Energy Transition Roadmap; OSeMOSYS, Open-Source energy Modelling System; PVGIS, Photovoltaic Geographical Information System; RE, Renewable Energy; SEI, Stockholm Environment Institute; TIMES, The Integrated Market Allocation-Energy Flow Optimisation Model System; TMY, Typical Meteorological Year; VRE, Variable Renewable Energy.

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https://doi.org/10.1016/j.esd.2025.101681
Received 18 December 2024; Received in revised form 15 February 2025; Accepted 17 February 2025

the total RE installed capacity, positioning it as the second most prevalent RE source after hydropower. Over the next thirty years, the solar PV sector has the potential to emerge as a major energy source. By developing additional solar farms, it could enable countries to meet around 25 % of global electricity demand by 2050 (Pourasl et al., 2023). The National Energy Transition Roadmap (NETR) of Malaysia targets a significant increase in RE share in installed capacity to 70 %, with 59 GW of solar PV in 2050 given its' high potential in the nation (Ministry of Economy, 2023). The objective of this paper is to investigate future projections of the Malaysia's national electricity system using five models built based on the Malaysian Renewable Energy Roadmap (MyRER) (Sustainable Energy Development Authority (SEDA) Malaysia, 2021) by SEDA Malaysia and the NETR (Ministry of Economy, 2023) by the Ministry of Economy, Malaysia from 2020 to 2050. The projected rising demands of fuel and electricity were calculated based on the projections specified for Malaysia in the IEEJ Outlook 2018 by the Institute of Energy Economics, Japan (The Institute of Energy Economics, Japan, 2017). The findings from this research will discover how the electricity supply and demand will evolve in Malaysia towards 2050 with higher electricity demands due to projected population growth, lower coal power plant capacities, higher penetrations of solar PV, and energy storage system (ESS) integration. However, as solar PV is highly intermittent due to variations in sunlight availability, the electricity generation from solar PV results in low-capacity factors. This generation could potentially lead to mismatches between electricity supply and demand, particularly during peak demand or peak generation periods. Therefore, as the national roadmaps target a significant increase in solar PV capacities for Malaysia towards 2050, the Malaysian government aims to deploy utility-scale BESS to curb mismatch issues in electricity supply and demand (Suruhanjaya, 2021). Based on the specifications in (Tian et al., 2018), there will be stability issues when RE penetration surpasses 30 % of peak demand. With the 70 % RE share target set in 2050, the solar power penetration will surpass the Malaysian Grid System Operator (GSO) limit of 24 %. This indicates that grid infrastructure upgrades and BESS integration will be needed for stability management of the Malaysian national grid in the future (Tee et al., 2024).

This paper investigated the techno-economic-environmental impact of RE transition in Malaysia by the development of five national-scale LEAP models with focus on Malaysia's power sector transition from 2020 to 2050. These five static models represented the following target years based on the roadmaps: Model 1 (Ref 2020), Model 2 (MyRER BaU 2025), Model 3 (MyRER NCT 2035), Model 4 (NETR 2040), and Model 5 (NETR 2050/NETR 2050 OPT). Analyses were carried out to evaluate the enhancement in performance parameters of models such as annual RE generation and CO2 emissions towards 2050. This study primarily examined the power sector, analysing the electricity balance of various sources to assess the impact of increasing solar PV in the national power mix towards the future. A sustainable transition in energy system models was presented, designed to gradually eliminate coal power plants in accordance with energy targets, while harnessing Malaysia's significant untapped RE potential. With this, the following research questions were addressed:

a) Which energy sources contribute to a sustainable primary energy supply, and how does the generation pattern of these technologies interact as the share of VRE in the Malaysian national power mix increases towards 2050?

b) Will the growth of RE, combined with the phased removal of coal, be adequate to match the rising electricity demand towards 2050?

c) Given the low-capacity factors of VRE, what amount of electricity discharge from ESS and additional imports will be technically required to meet demand during periods in which energy generation falls short in the future years?

d) How much large-scale ESS capacity will be required in 2050 to ensure that electricity generation meets demand and prevents excess generation throughout the entire year?

e) How would the total power sector related CO2 emissions evolve in the industry, residential, commercial, agriculture, and transport sectors from 2020 towards 2050?

Based on the literature reviewed, there were limited publications on the LEAP-NEMO framework and ESS in Malaysia's national power mix towards 2050. Research on the deployment of large-scale BESS in Malaysia is still limited, though pilot projects are expected in the coming years. Additionally, a thorough investigation is underway to assess the ESS capacity required to accommodate significant levels of solar energy integration in the country (Tee et al., 2024). Gaps were identified as there were limited studies in the analyses of Malaysia's hourly time-sliced electricity supply and demand in the power sector towards the future, by using LEAP-NEMO optimisation with energy storage based on static models (target year). To address these gaps, LEAP-NEMO optimisation was carried out to determine the optimal capacities of BESS and PHS based on the NETR 2050 model with analysis of static models and long-term models.

This paper contributes to the existing literature on LEAP methods through the development of five models for Malaysia to analyse the changes in electricity balance in the national power mix from 2020 to 2050. This study offers insights into the challenges and opportunities for Malaysia in energy planning and potentially moving towards net-zero emissions by 2050. Analysis of the electricity balance were carried out in the models considering the rise in electricity and primary fuel demands, increasing shares of natural gas and RE with the phasing out of coal, integration and optimal design of BESS and PHS, and energy efficiency for electricity demand reduction.

Literature review of energy system modelling methods

Various researchers have examined the key distinctions among available energy models. Notably, Prina et al. (Prina et al., 2021) conducted a review focused on bottom-up energy system models used at the island level. Connolly et al. (Connolly et al., 2010) conducted a review of over 68 energy models that can be used to explore RE integration systems. Their study highlighted the LEAP model as a comprehensive tool, capable of simulating technologies and costs across all energy sectors, including electricity, transportation, and heating. Ringkjøb et al. (Ringkjøb et al., 2018) discussed the LEAP model in their review, highlighting its numerous features compared to other energy models.

Based on this review section, LEAP was chosen in comparison to other models based on the following criteria: It has a projection range spanning from 20 to 50 years and is well-suited for energy modelling at national geographical coverages. It is characterised as a hybrid or integrated model and has the flexibility to model both static and long-term approaches. It can account for both the energy and non-energy sectors GHG emissions. With recent updates in the model, LEAP can simulate high temporal resolution data (8760 hourly sets) but computational time would be increased. Therefore, the high temporal resolution datasets were imported into LEAP to formulate the equivalent 96 hourly averaged time-slices based on four quarters of a year. Energy storage and least cost optimisation pathways can be carried out with NEMO being recently added to LEAP. Finally, the modelling outputs of this tool are focused on the performance parameters required for this study such as, electricity generated, storage capacity, sectoral GHG emissions, and total costs.

Shakya et al. (Shakya et al., 2023) employed LEAP to analyse Nepal's newly implemented 'Long-term Strategy for Net-zero Emissions' and assessed its reductions in air pollution and enhancements in energy security. In comparison to the reference scenario, the net-zero CO2 emissions scenario is projected to cut air pollutants by 70 % for Organic Carbon and 85 % for Black Carbon by 2050. Additional research could focus on quantifying the health benefits and the impact on agricultural productivity resulting from reduced environmental emissions in a net-zero scenario.

Kanugrahan and Hakam (Kanugrahan & Hakam, 2023) used LEAP-NEMO to assess the viability of Indonesia achieving its net-zero emissions goal by 2060 through a future power generation model that relies on RE. To achieve this goal, Indonesia must retire its current fossil-fuel power plants and increase the development of RE facilities. Gaps can be further investigated to identify the most cost-effective approach for ESS integration. Additionally, it will be important to include transmission capacity and perform spatial analyses of individual power plants and substations, requiring further modelling efforts.

Ozawa et al. (Ozawa et al., 2022) explored different scenarios for Japan's future energy systems to achieve net-zero CO2 emissions by 2050 with MARKAL. To achieve carbon neutrality by 2050, Japan must fully decarbonise its electricity generation by 2040. This implies that RE should lead the decarbonised energy sector, and CO2 removal technologies will be necessary if reducing emissions in industry proves difficult. Gaps can be investigated on how socioeconomic elements play a role in reaching carbon neutrality; thus, examining assumptions related to economic and population growth rates is essential, as they can significantly influence future energy demand.

Akpahou et al. (Akpahou et al., 2024) projected Benin's future energy needs while aiming to lower GHG emissions and identify alternative strategies to overcome obstacles to clean energy adoption. LEAP was employed to analyse projected energy demand and emissions for the country in four scenarios. The findings indicate that, under the BaU scenario, total energy demand is projected to rise to 445 PJ by 2050, up from the current level of approximately 164 PJ. In this scenario, GHG emissions are anticipated to reach 21 Mt. CO2e by 2050.

Handayani et al. (Handayani et al., 2022) assessed strategies for achieving net-zero emissions in the power sector by 2050 for ASEAN using LEAP-NEMO. It was determined that ASEAN countries need to harness their currently underutilised RE resources promptly to reach net-zero emissions by 2050. Based on the findings, GHG emissions are expected to rise until they peak in 2029, after which they will gradually decrease to zero by 2050. Gaps can be explored in the net-zero power sector pathway for ASEAN, considering enhanced grid interconnections for power exchange between member countries.

Ren et al. (Ren et al., 2024) introduced a LEAP-REP model for RE integration to assess the feasibility of achieving net-zero emissions by 2050 in China's power sector. The power sector can potentially reach net-zero emissions by 2050 while accommodating the increasing electricity demand with an RE penetration rate of 75 %. Since the model mainly focuses on optimising capacity expansion and electricity supply based on cost, it places less emphasis on system reliability, particularly neglecting the effects of extreme weather events. As climate change increases the frequency of such events, future updates to the model will include additional reliability constraints.

Wambui et al. (Wambui et al., 2022) examined how alternate electricity development scenarios affect system costs and GHG emissions in Kenya. The research utilised LEAP-NEMO to determine the optimal energy mix. From the findings, integrating RE resources with ESS resulted in cost savings, reduced CO2 emissions, and improved security for Kenya's power infrastructure in the future. The alternative energy planning scenarios have the potential to greatly lower both GHG emissions and overall system costs.

Cai et al. (Cai et al., 2023) evaluated four scenarios based on the municipality of Bengbu in attaining carbon neutrality and formulated a low-emission framework using LEAP, considering local economic conditions, population, energy, and transportation. The findings offer valuable perspectives on energy transformation options from 2020 to 2060. The findings indicated that increased industrial electrification rates, phasing out coal generation, adoption of RE, and CCUS are key to meeting carbon reduction targets. Gaps on ESS technology and its effect on total costs of the system can be investigated.

Ayuketah et al. (Ayuketah et al., 2022) assessed the impact of Cameroon's sustainability initiatives on the nation's energy system towards 2045 using LEAP-NEMO. This study found that the alternative scenarios exceed the BaU scenario in terms of avoided installed capacity, financial savings, and reduced GHG emissions. Gaps can be investigated on the higher temporal and spatial resolution to more accurately capture the interaction between the short-term RE fluctuations and long-term generation expansion planning.

Calikoglu and Koksal (Calikoglu & Aydinalp Koksal, 2023) outlined a strategic framework using LEAP for advancing the Turkish public electricity and heat generation industries aimed at achieving net-zero emissions. From the findings, Turkey needs to implement significant reforms in its energy policies to facilitate substantial investment in nuclear, RE and CCUS. Consequently, it is essential to identify additional potential storage locations, engage in regional collaboration with neighbouring countries on storage solutions, and plan for the utilisation of captured carbon.

Malka et al. (Malka et al., 2023) examined energy demand across Norway's households, industrial sector, transportation, and other areas using LEAP. The study concluded that achieving net-zero targets by 2050 is unlikely without the introduction of a carbon tax and the deployment of CCUS technologies, especially within the oil and gas industry. The upcoming efforts will focus on optimising the entire energy system in Norway through multicriteria decision-making approaches.

Li et al. (Li et al., 2024) developed the LEAP-CHINA model to project China's energy demand across various scenarios from 2022 to 2060. A key finding from the study indicated that there is a clear trend towards decarbonising the power system and electrifying the energy system, with non-fossil energy generation projected to make up 78 % to 82 % by 2060. Gaps can be further investigated in analysing projections of CO2 emissions towards 2060.

Gebremeskel et al. (Gebremeskel et al., 2023) introduced the inaugural comprehensive model of Ethiopia's electricity system by integrating the OSeMOSYS and LEAP frameworks to explore pathways for power supply and demand towards 2050. The analysis indicated that enhancing efficiency within the electricity system will be crucial for shaping future energy investment strategies. By making minor adjustments, the findings and policy insights can help explore and guide national and regional power sector development in similar contexts.

Wang et al. (Wang et al., 2023) employed the LEAP-NEMO optimisation model to examine the most cost-effective decarbonisation pathways for the power sector in Inner Mongolia. The results demonstrated that it is feasible to achieve significant emission reductions at minimal cost. Gaps can be investigated in the uncertainty of prediction results by addressing the improvement in model time resolution based on accurate data.

Babatunde et al. (Babatunde et al., 2021) developed a computational economic model to analyse the dynamics of Malaysia's electricity sector under different scenarios from 2015 to 2050. Their findings revealed that removing natural gas subsidies alone will not significantly cut CO2 emissions, as it would likely lead to a shift from low-carbon technologies to coal-fired power. Gaps can be explored in the incorporation of solar PV to improve RE generation fraction in demand matching. This could enable complete phasing out of coal and reduction in CO2 emissions resulting from natural gas power generation towards 2050.

Material and methods

Low Emissions Analysis Platform (LEAP) Model

This study uses LEAP developed by the Stockholm Environment Institute (SEI) to develop alternative national-scale energy system models for Malaysia with its distinct data structures. LEAP accommodates diverse modelling techniques, including both top-down macroeconomic models and bottom-up end-use accounting methods for assessing energy demand. Additionally, LEAP offers significant flexibility in analysing energy demand, allowing for data to be examined at various levels, from broad aggregate assessments to detailed, end-use-specific frameworks (Heaps, 2022). LEAP processes its results through two primary stages: accounting and optimisation. During the accounting phase, it projects future energy demand for each sector throughout the study period using the provided input data. It also determines the total energy supply required to satisfy this increasing demand, including considerations for network reserve margins and energy losses. Notably, this stage does not propose specific technological capacities (Masoomi et al., 2022). The final stage involves optimisation based on either environmental impacts or a comprehensive cost-benefit analysis. Fig. 1 illustrates the methodology process flowchart of the development of alternative LEAP models for Malaysia towards 2050.

Modelling of electricity and fuel demands

For the demand modelling of Malaysia in LEAP, secondary data collection of the electricity demand in the industrial, residential, commercial, transport, and agriculture sectors was obtained from IEA (International Energy Agency, 2020). Fig. 2 illustrates the growth in electricity demand across all sectors based on the calculated projections towards 2050. This input data has been used to represent the disaggregated electricity demand by sectors within the models.

The annual electricity demands and primary fuel demands for energy consumers were calculated from 2020 (base year) to 2050 based on the respective CAGR specified in IEEJ Outlook 2018 (The Institute of Energy Economics, Japan, 2017) for the projection of future demand values. Fig. 3 illustrates the projection growth of the primary fuel demands for the five models. For the annual hourly distribution of electricity demand throughout the year, high temporal resolution data (8760 sets) for Malaysia in 2020 were obtained from the GSO of Malaysia via real-time IEA (Grid System Operator, 2024; International Energy Agency, 2022). This high temporal resolution dataset was imported into LEAP to model the time-varying yearly shapes of electricity demands in 96 hourly averaged time slices based on four quarters of a year. These time slices represented the hourly average of electricity demand in four quarters of a year. Fig. 4 illustrates the hourly high-temporal resolution data of electricity demand in Malaysia. The plot of this data was extracted from January 2020 from the entire year's dataset for illustration.

Modelling of energy supply and transformation

Once modelling the demand is completed, LEAP begins evaluating energy supply resources and transformation technologies. This analysis stage focuses on the various methods used to convert different energy sources into electricity. This assessment considers both current and anticipated facilities available during the study period. Consequently, detailed performance parameters for each technology are provided, including plant capacities, availability, efficiencies, historical energy production, capacity credit, dispatch rules, and the types of fuel used. The LEAP algorithm applied in the net energy consumption for transformations (Emodi et al., 2017) is:

$$ET_s = \sum_m \sum_t ETP_{t,m} \, X \left(\frac{1}{f_{t,m,s}} - 1 \right) \tag{1}$$

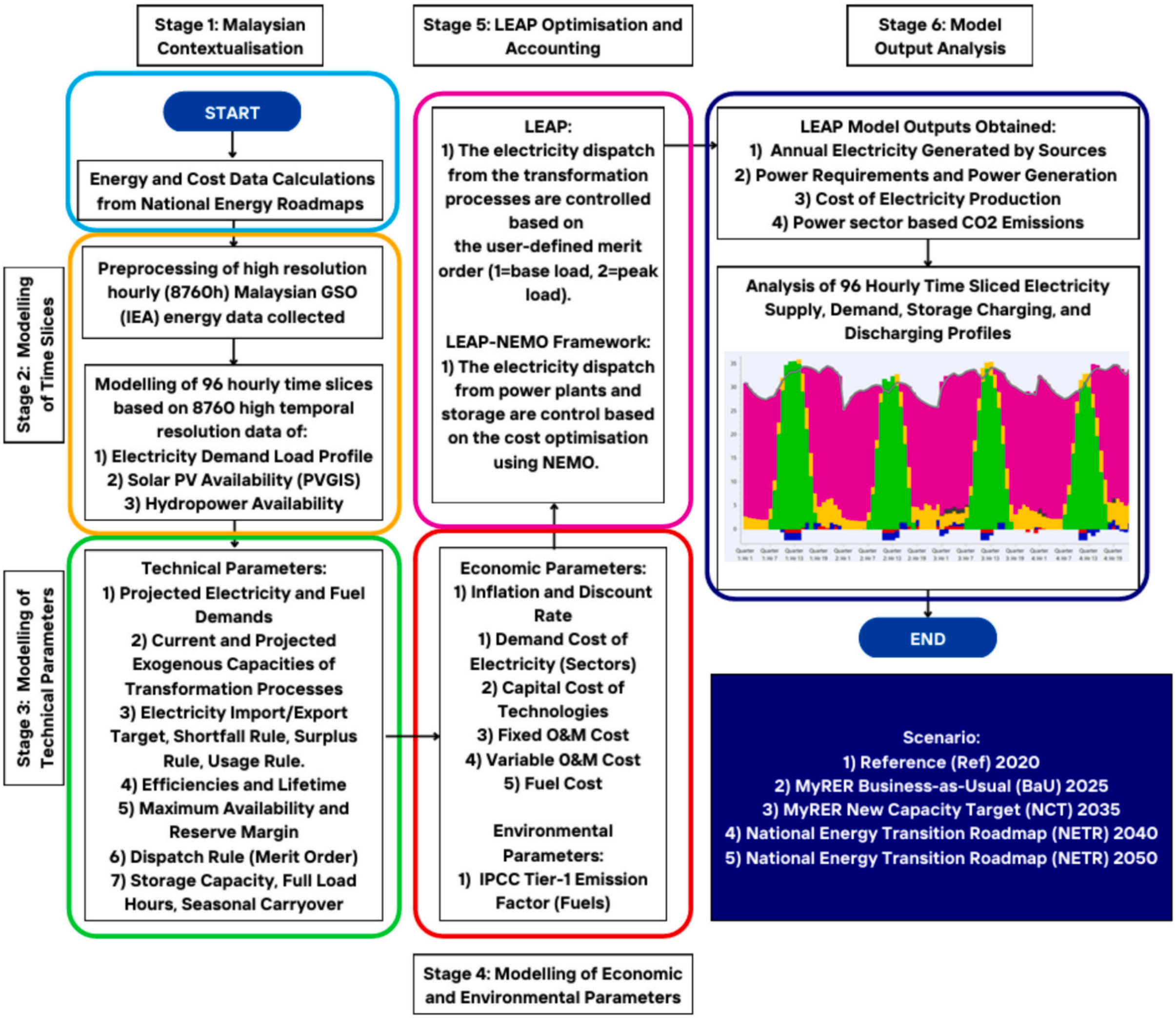

Fig. 1. Methodology Stages of LEAP Model Development and LEAP-NEMO Optimisation for Malaysia Case Study.

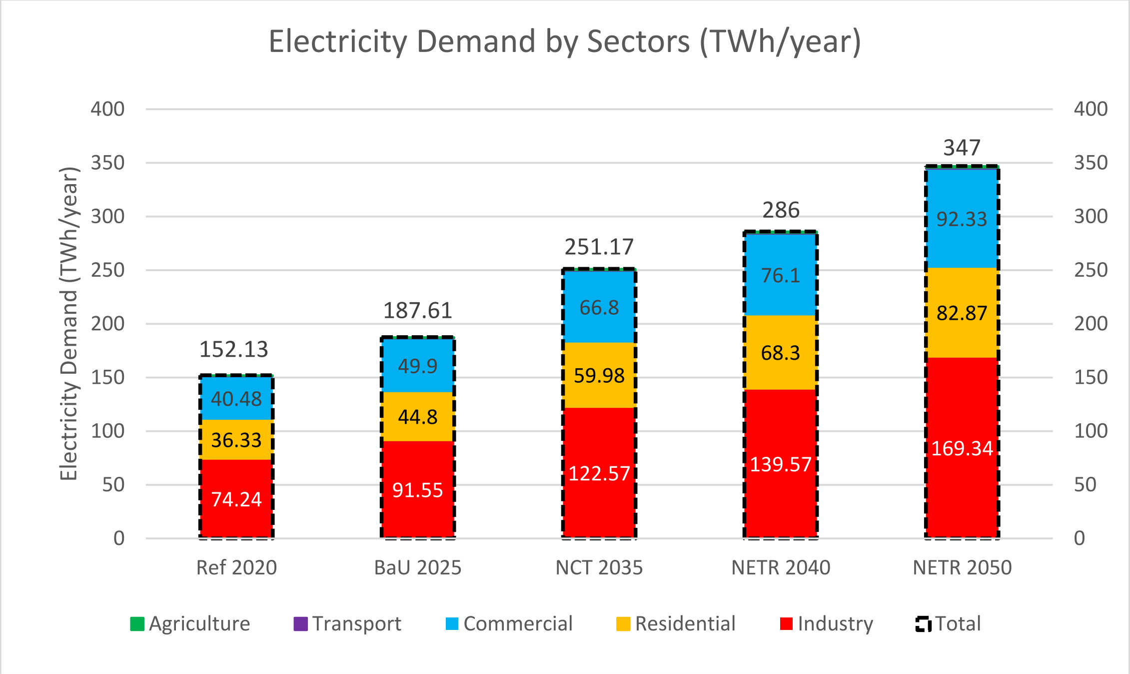

Fig. 2. Calculated values of electricity demand across various sectors towards 2050.

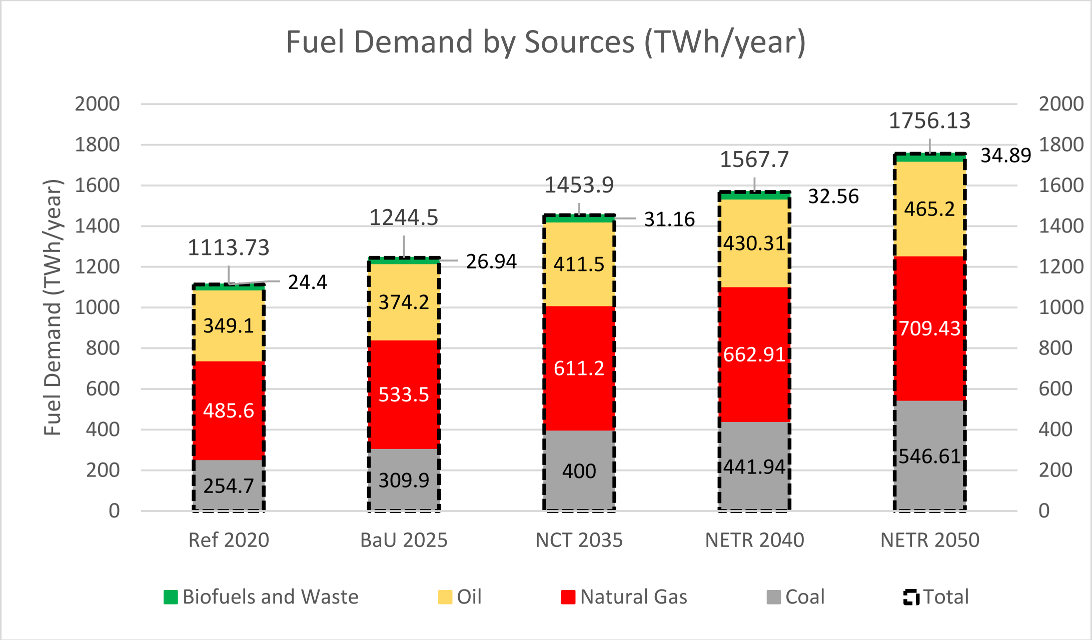

Fig. 3. Calculated values of primary fuel demand by sources towards 2050 (The Institute of Energy Economics, Japan, 2017).

where, (ET) denotes the energy transformation during the process of conversion, (ETP) denotes the energy conversion process product (e.g. electricity), (f) denotes the process efficiency of energy conversion defined in (%). (s) denotes the primary energy source (e.g. coal), (m) denotes the technology (e.g. gas turbine) and (t) denotes the secondary energy source.

The LEAP electricity generation module models the supply of electricity to satisfy specified demand levels, considering the specified input parameters. To determine the fuel needs for electricity production, the resources module utilises the data from the generation module. Key outputs of this model include added capacity, the electricity generation mix, hourly generation profiles, and CO_2 emissions associated with the power system transition. The simulation process for electricity generation consists of three main steps. Initially, LEAP calculates the necessary capacity expansion and reserve requirements to meet demand. This step yields the annual capacity additions and the technology mix. In the second step, LEAP allocates electricity production according to the load curve and annual demand, generating outputs for each process. Finally, the resource module assesses the primary energy needed and GHG emissions for each technology based on fuel efficiency (Handayani et al., 2023). The transition of the installed capacity mix of energy sources in the Malaysian national energy infrastructure from 2020 to 2050 is illustrated in Fig. 5.

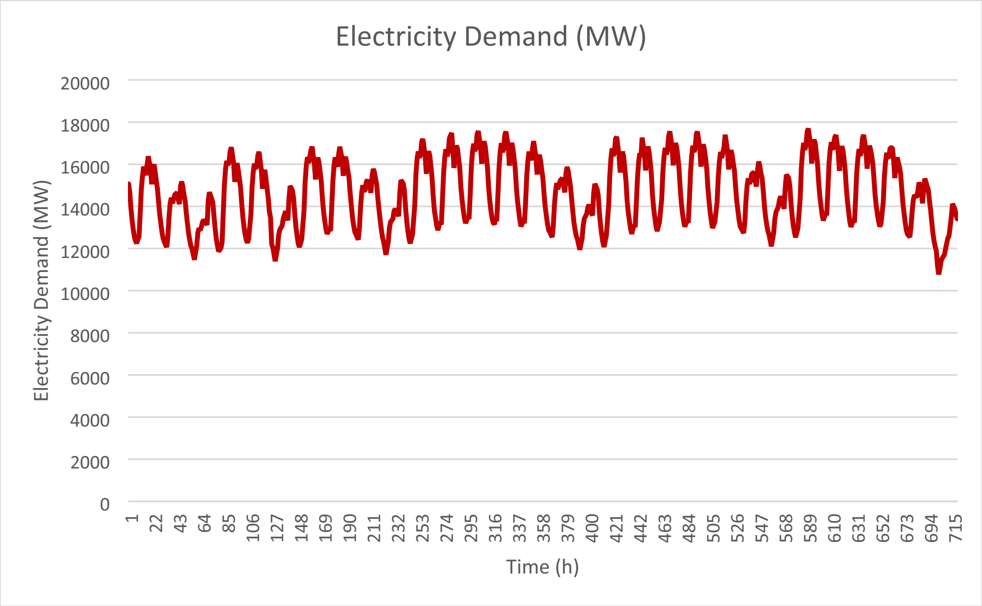

Fig. 4. High temporal resolution data of hourly electricity demand of Malaysia in 2020 (Grid System Operator, 2024; International Energy Agency, 2022).

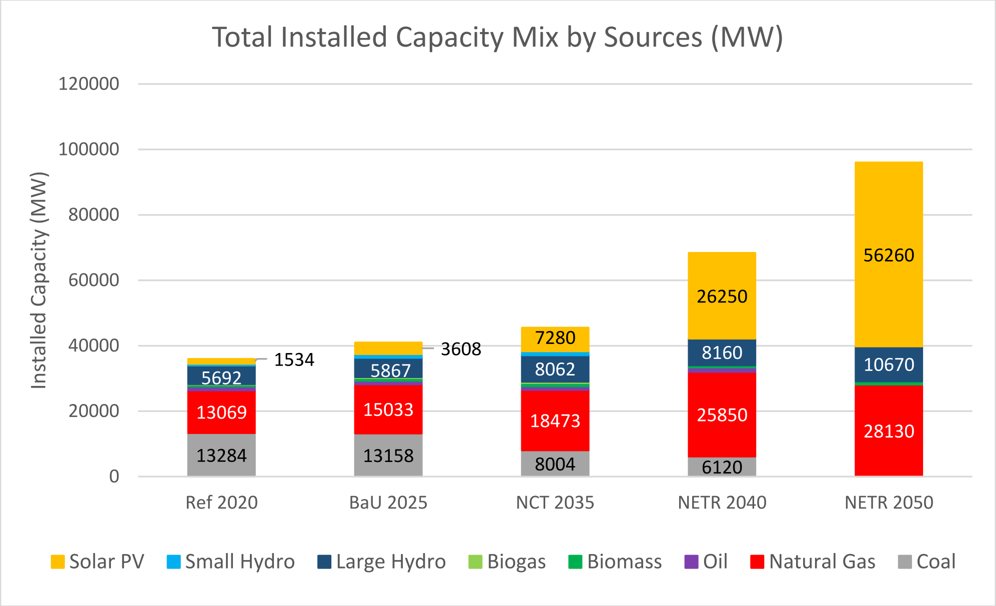

Fig. 5. Installed capacities of energy sources in the Malaysian energy mix from 2020 to 2050 based on the MyRER (Sustainable Energy Development Authority (SEDA) Malaysia, 2021) and NETR (Ministry of Economy, 2023).

The total installed capacity mix in 2020 was 38,002 MW mainly driven by coal (34.96 %) and natural gas (34.39 %). The main renewables present in the installed capacity mix are hydropower (16.31 %) and solar PV (4 %). Transitioning towards 2050, the total installed capacity is projected reach 98,080 MW mainly driven by solar PV (57.36 %), natural gas (28.68 %), and hydropower (10.88 %). From this transition, there will be a significant upscaling of solar PV from 2020 towards 2050 which could result in issues in energy supply and demand mismatch. ESS are modelled with the LEAP-NEMO framework to balance this high fraction of VRE. While coal is gradually phased out towards zero in 2050, natural gas is gradually upscaled due to energy security reasons in demand matching. The RE share in installed capacity increases from 23 % in 2020 to 70 % in 2050 in alignment with the targets set in the NETR.

Modelling of annual hydropower variability

The variable availability of hydropower throughout the year were modelled with hourly high temporal resolution data. The datasets for hydropower generation were obtained from the Malaysian GSO via IEA (Grid System Operator, 2024; International Energy Agency, 2022). This generation profile was extracted for a period of a month from an annum and is illustrated in Fig. 6. The high temporal resolution data obtained were formatted accordingly to be imported into LEAP to model the hydropower availability shape (0 to 100 %) throughout the 96 time slices in the year.

Modelling of annual solar PV variability

A technique from the Photovoltaic Geographical Information System (PVGIS) provided by the European Commission (European Commission,

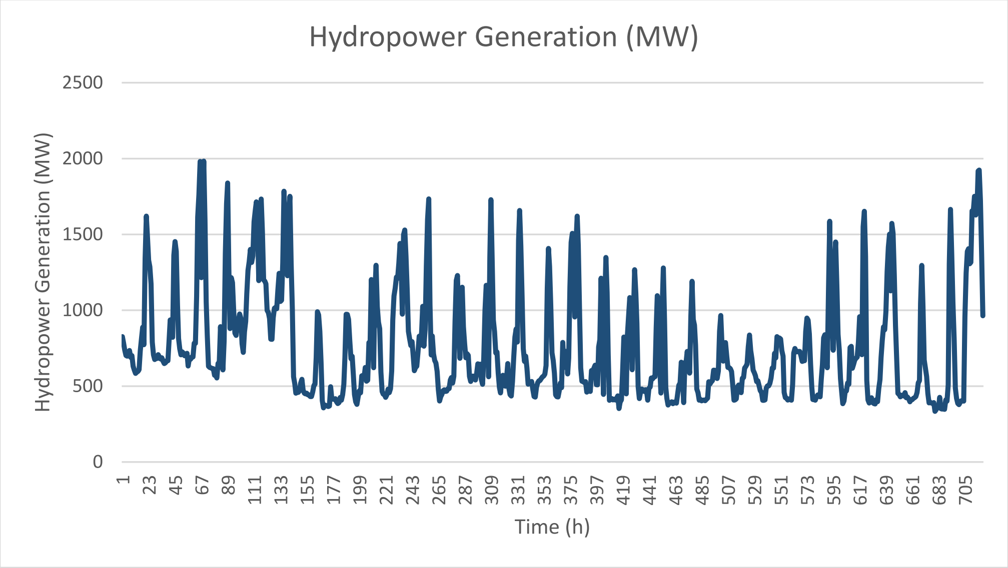

Fig. 6. High temporal resolution data of hourly hydroelectric power generation in Malaysia in 2020 (Grid System Operator, 2024; International Energy Agency, 2022).

2024) was utilised to estimate the high temporal (8760 h) resolution hourly energy output of each large-scale solar (LSS) plant across each Malaysian states throughout the year. This system facilitated the acquisition of detailed temporal solar radiation and power generation profiles for each LSS facility in Malaysia, in accordance with the capacity data from the Energy Commission (Energy Commission, 2024a) as shown in Fig. 7. PVGIS offers hourly data on photovoltaic power generation and solar radiation throughout the year and can produce Typical Meteorological Year (TMY) data, which encompasses solar radiation, temperature, and other meteorological variables. The PVGIS-SARAH solar radiation database was chosen due to its comprehensive coverage of Malaysia and its satellite-based spatial resolution of 5 km. Fig. 8 illustrates the hourly solar PV generation results which was extracted for a month from the annual hourly dataset. The high temporal resolution data obtained were formatted accordingly to be imported into LEAP to model the solar PV availability shape (0 to 100 %) throughout the 96 time slices in the year.

NEMO and energy storage modelling

NEMO, a recent addition to LEAP, is a high-performance, open-source energy system optimisation tool developed in the Julia programming language. It models energy systems with the optimal foresight, focusing on least-cost optimisation to meet electricity demand over time. Key features of NEMO relevant to this study include its capability to model RE targets, and its advanced simulation of energy storage while accounting for VRE profiles. This functionality supports robust climate change planning and a detailed analysis of energy storage roles (Stockholm Environment Institute & NEMO model concept, 2021). Daily electricity demand patterns and the maximum availability of each power generation technology inform the simulation of energy storage in NEMO. The maximum availability, expressed as a percentage, represents the ratio of actual energy produced to the potential energy that would have been generated if the technology operated at full capacity throughout a given period. NEMO can operate on various solvers such as CPLEX, HiGHS, Cbc, GLPK, Mosek, and Gurobi. For the optimised NETR 2050 model with lithium-ion BESS and PHS, optimisation with NEMO

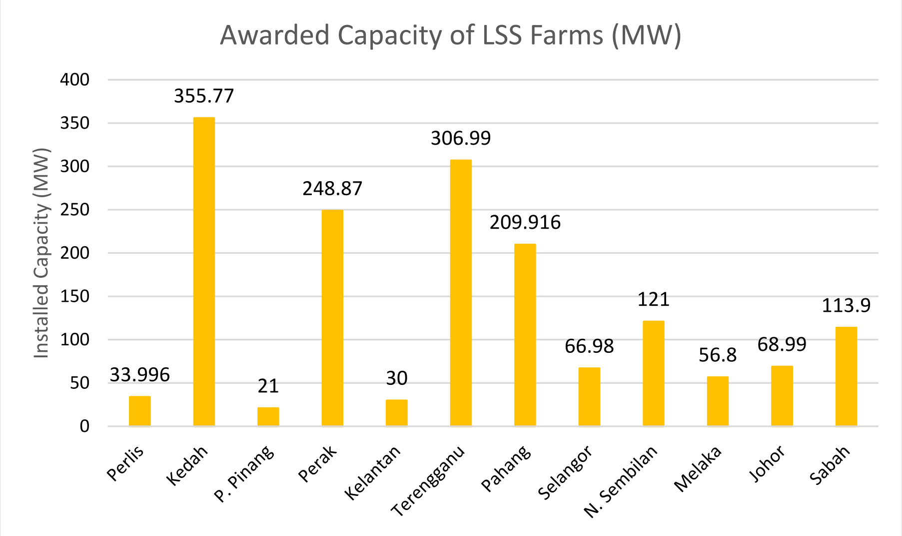

Fig. 7. Awarded capacities of LSS farms in Malaysian States based on the Energy Commission (Energy Commission, 2024a).

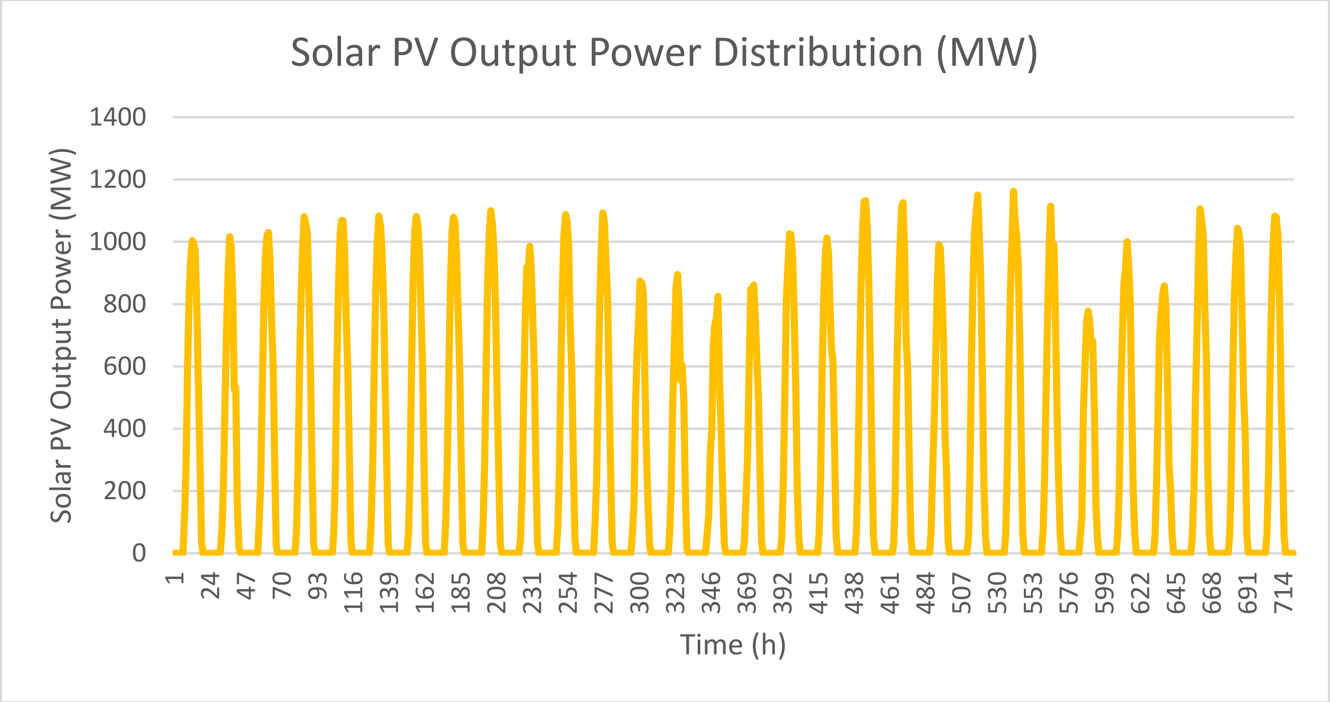

Fig. 8. High temporal resolution data of hourly solar power generation in Malaysia.

and the fastest installed solver (HiGHS) as per simulation date was carried out.

Carbon emissions factor

The energy conversion-based carbon emissions are calculated in LEAP with the following Eq. (El-Sayed et al., 2023):

$$CET_n = \sum_s \sum_m \sum_t ETP_{t,m} \, X \left(\frac{1}{f_{t,m,s}} \right) X \, EF_{t,m,s} \tag{2}$$

where, (CET) are the carbon emissions from energy conversion, ETP is the product of energy conversion. (EF) is the fuel emissions factor during the conversion of energy from primary type(s) to secondary type (t) through technology (m) with an efficiency (f). LEAP is used to estimate the emissions from the fuel sources in the Malaysian models that were developed to evaluate their impact on the environment. This is done by utilising the emissions factors obtained from The Intergovernmental Panel on Climate Change (IPCC) Tier 1 Default Emission Factors stored in the TED database for each sub-bituminous coal, natural gas, oil, and biomass.

Economic modelling

The economic data for Malaysia such as the GDP, inflation rate, and discount rate were obtained from the World Bank Group as shown in Table 1.

The economic data for the electricity demand costs were obtained from Tenaga Nasional Berhad (TNB) (Tenaga Nasional Berhad, 2023; Tenaga Nasional Berhad, 2024a; Tenaga Nasional Berhad, 2024b) based on the pricing and tariff values in the industrial, domestic, commercial, agriculture, and transport sectors and these values are specified in Table 2. The tariffs were averaged based on the peak and off-peak periods followed by the specific voltage levels (low voltage, medium voltage, and high voltage) for the five sectors. For the domestic sector, the price for the five tariff categories were averaged.

The economic data for the transformation processes which were the capital costs of technologies, fixed operation and maintenance (O&M) costs, variable O&M costs, and fuel costs were used to develop the LEAP energy system model for the supply side. Country specific data for Malaysia were used whenever possible rather than mean values of all countries. Most of these data were obtained from country reports, energy sector development plan outlooks and academic research related to LEAP model development for ASEAN countries. These sources were IEA (IEA, 2020), TNB (Tenaga Nasional Berhad, 2024c), Energy Commission (Energy Commission, 2024b), ASEAN-RESP, 2016 (ASEAN-RESP, 2016), U.S Energy Information Administration (EIA) (U.S. Energy Information Administration, 2022), Handayani (Handayani et al., 2023), and Zakeri and Syri (Zakeri & Syri, 2015) as shown in Table 3.

Table 1
Data of GDP, Inflation Rate, and Discount Rate (The World Bank Group, 2023; The World Bank Group, 2024).

Economic Parameter	Value
Gross Domestic Product, GDP (USD)	337.46 billion
Inflation Rate (%)	2.5
Discount Rate (%)	4.8

LEAP results

This section details the results of LEAP models developed for the five Malaysian models. The analyses evaluate these models based on these key performance parameters: 1) annual electricity production (TWh/year), 2) hourly electricity power generation (MW), 3) GHG emissions

Table 2
Data of Electricity Demand Costs (Tenaga Nasional Berhad, 2023; Tenaga Nasional Berhad, 2024a; Tenaga Nasional Berhad, 2024b).

Electricity Sector	Tariff Rates (cents/kWh)
Industry	7.9
Domestic	10.6
Commercial	9.14
Agriculture	8.5
Transport	34.16

Table 3
Capital, Fixed and Variable O&M, and Fuel Costs.

Source	Technology	Lifetime (Yr)	Capital Cost (USD/kW)	Fixed O&M Cost (USD/kW)	Variable O&M Cost (USD/kWh)	Fuel Cost (USD/t)
(IEA, 2020; Tenaga Nasional Berhad, 2024c)	Coal	30	1897	60	0.13	127.75
(IEA, 2020; Energy Commission, 2024b)	Natural Gas	30	823	48	4.7	31.6
(ASEAN-RESP, 2016)	Hydro	50	2640	55.44	0.96	–
(ASEAN-RESP, 2016)	Solar	25	1987	17.883	0	–
(ASEAN-RESP, 2016)	Biomass	25	2740	137	8.63	6.82
(Diesel Fuel Statistical Agency, 2024; U.S. Energy Information Administration, 2022)	Oil	30	2018	36.81	5.96	495
(Zakeri & Syri, 2015)	Li-ion Battery	20	1299	7.73	2.34	–

(Mt CO2e), and iv) total net present value from 2020 to 2050.

Annual electricity generation

The total annual electricity generation by sources based on the five models are illustrated in Fig. 9.

In Model 1, the total electricity generation was at 153.8 TWh/year which are generated by coal (43.76 %), natural gas (43.04 %), hydro (6.11 %), oil (3.9 %), biomass (2.34 %), and solar (0.91 %). In Model 5 (NETR 2050), this value was projected to be at 347 TWh/year with contributions mainly from natural gas (63.78 %), followed by solar (17.4 %), hydro (7.3 %), biomass (2.2 %), and additional imports (9.33 %). With energy efficiency and LEAP-NEMO optimisation, Model 5 was improved to eliminate the dependency on additional imports required to match the demand. This resulted in a total annual electricity generation of 270.6 TWh/year with contributions from natural gas (58.98 %), solar PV (31.23 %), hydropower (9.53 %), and biomass (0.26 %). There was a higher fraction of electricity generated by renewables as the merit order dispatch of the solar was configured to be operating at its full capacity in addition to the optimisation with ESS.

Hourly electricity power generation

The hourly electricity generation by sources were simulated in LEAP based on the 96 time slices formulated from the high temporal resolution datasets. The hourly power generation pattern aligned with the demand curve throughout the year, and the order of power dispatch was determined by the merit order assigned to each technology. LEAP controls the electricity dispatch from each generation source based on the merit order defined. The hourly generation for Models 1 to 5 are illustrated in Fig. 10–14 respectively.

In Model 5, the demand will not be fully met by the energy sources and additional electricity import is required to meet this demand. Therefore, modelling energy efficiency for electricity demand reduction in the industrial, residential, and commercial sectors were carried out based on the percentage reduction values specified in the NETR. This was followed by LEAP-NEMO optimisation with the integration of BESS and PHS. Fig. 15 illustrates the hourly supply and demand generation profile and Fig. 16 illustrates the same profile with the charging and discharging processes of the BESS and PHS.

In this optimised model, solar PV was configured to be dispatched at its full capacity whereas the other power plants were configured based on the merit order of dispatch. This was enabled to increase the fraction of RE generated and reduce dependency on natural gas power plants during the day time periods. Based on the hourly results, the electricity generation of solar PV exceeds the demand during Hr 10 to Hr 14. The Li-ion BESS and PHS stores the excess energy during these periods. The peak charging of BESS and PHS were 1443.8 MW and 849.2 MW respectively. During periods between Hr 15 and Hr 24, solar PV generation begins to decrease and there are periods in which the demands are

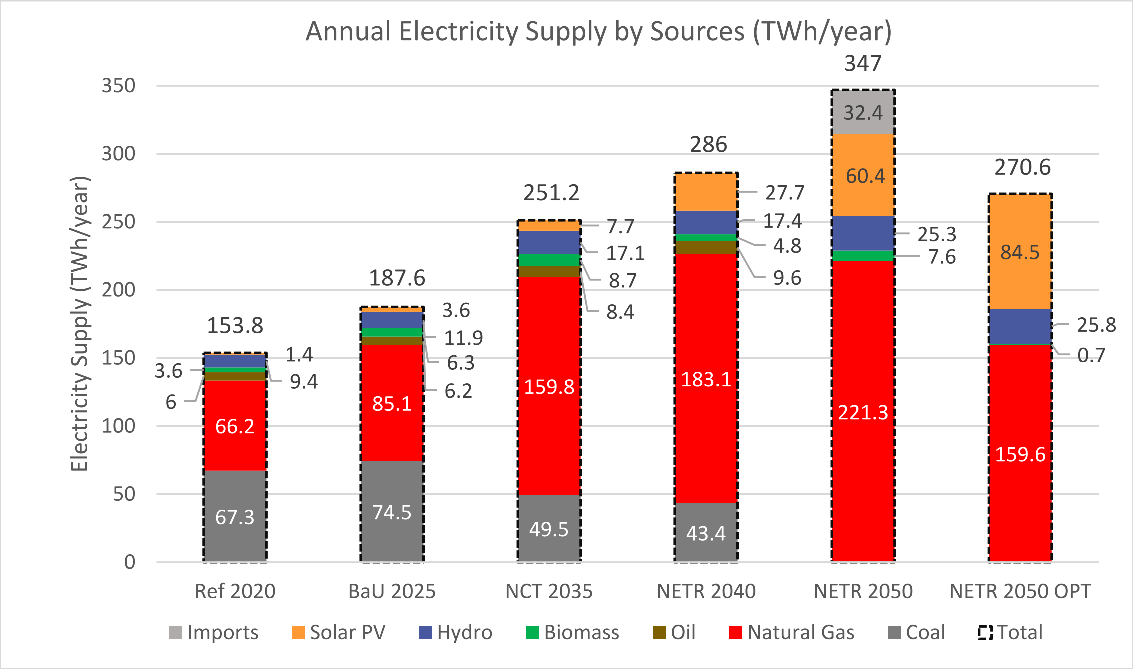

Fig. 9. Total annual electricity generation by sources for the models.

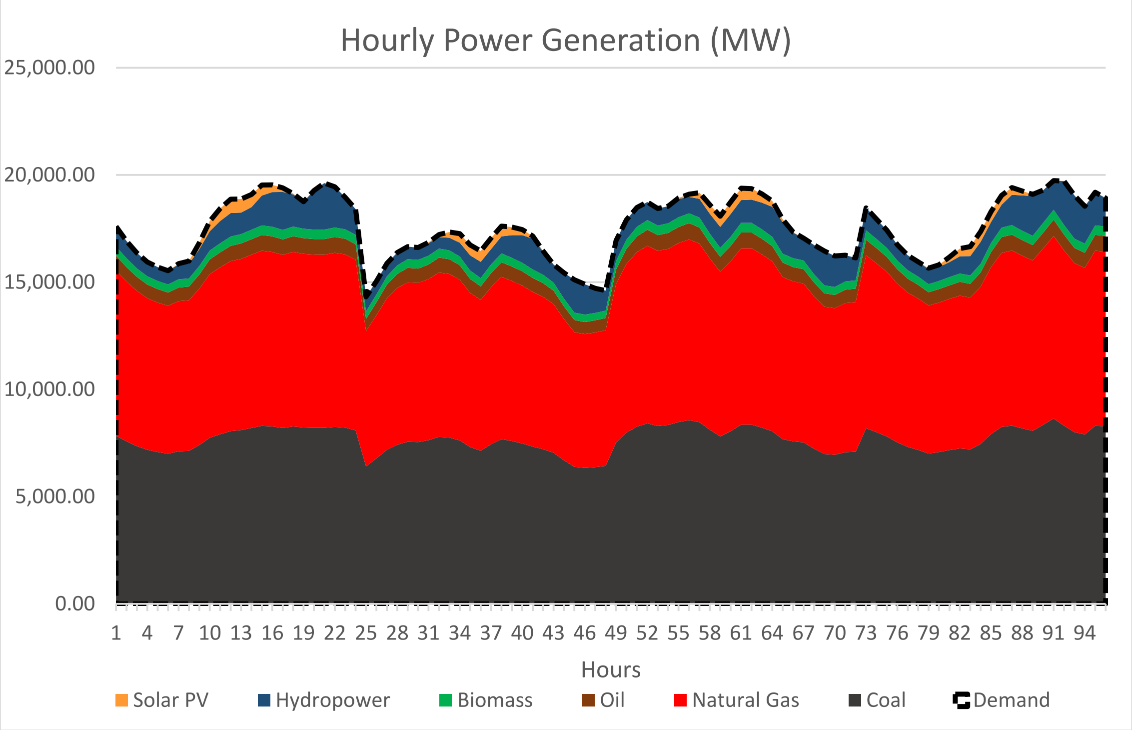

Fig. 10. Hourly Power Generation in Model 1.

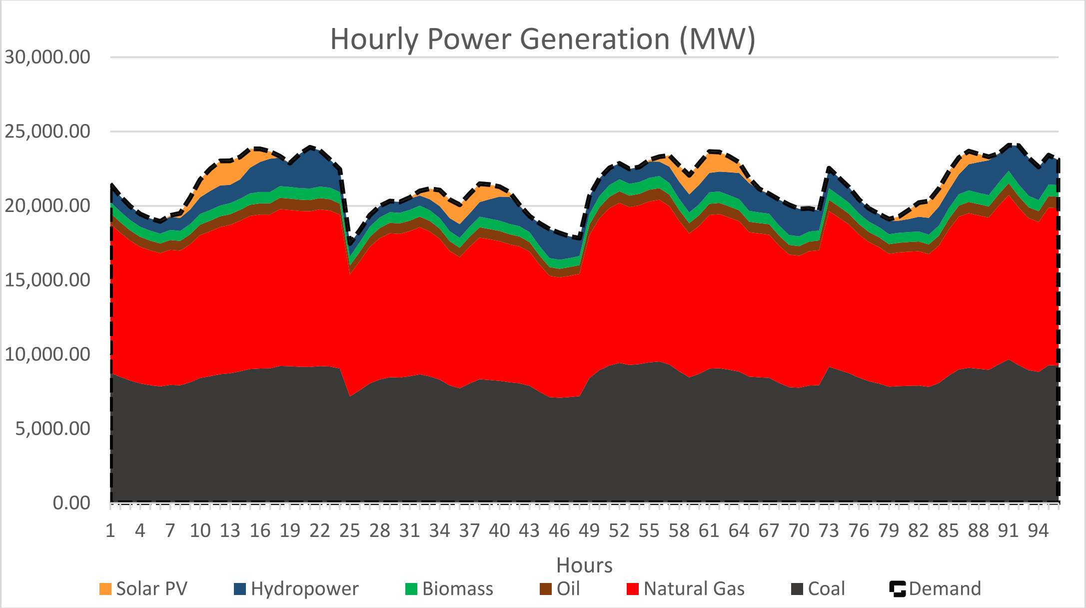

Fig. 11. Hourly Power Generation in Model 2.

not met by the energy sources. The ESS contributes to discharge the stored energy during these periods to match the demands. The peak discharge of the BESS and PHS was 1357.2 MW and 645.4 MW respectively. Table 4 specifies the optimal technological parameters for the two ESS technologies after LEAP-NEMO optimisation. In terms of total energy generation results throughout the year, the BESS and PHS resulted in −134.6 GWh and − 263.2 GWh respectively.

Greenhouse Gas (GHG) Emissions

Fig. 17 illustrates the GHG emissions resulted from electricity generation in the power sector based on the type of fuel used in the five models.

The total power sector-based GHG emissions from Model 1 was 83.2 Mt. CO2e driven by coal (60.2 %), natural gas (35.6 %), oil (4.2 %), and biomass (0.1 %). Model 5 (NETR 2050) projected 99.1 Mt. CO2 mainly driven by natural gas (99.8 %), followed by biomass (0.2 %) and this improved to 71.3 Mt. CO2, fully driven by natural gas (100 %) after LEAP-NEMO optimisation. For the total emissions in all sectors, the results for models 1 to 5 resulted in 287.5, 321.5, 382.1, 404.5, and 466.3 Mt. CO2 respectively. With LEAP-NEMO optimisation, model 5 was improved to be at 449.7 Mt. CO2 mainly due to the power sector.

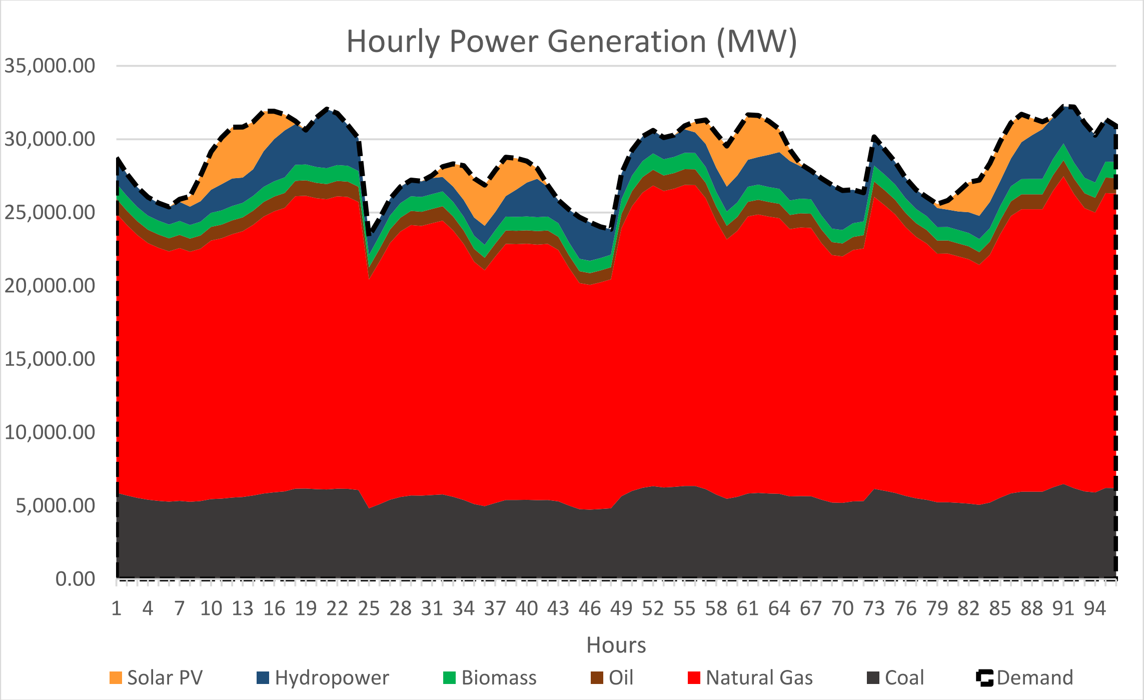

Fig. 12. Hourly Power Generation in Model 3.

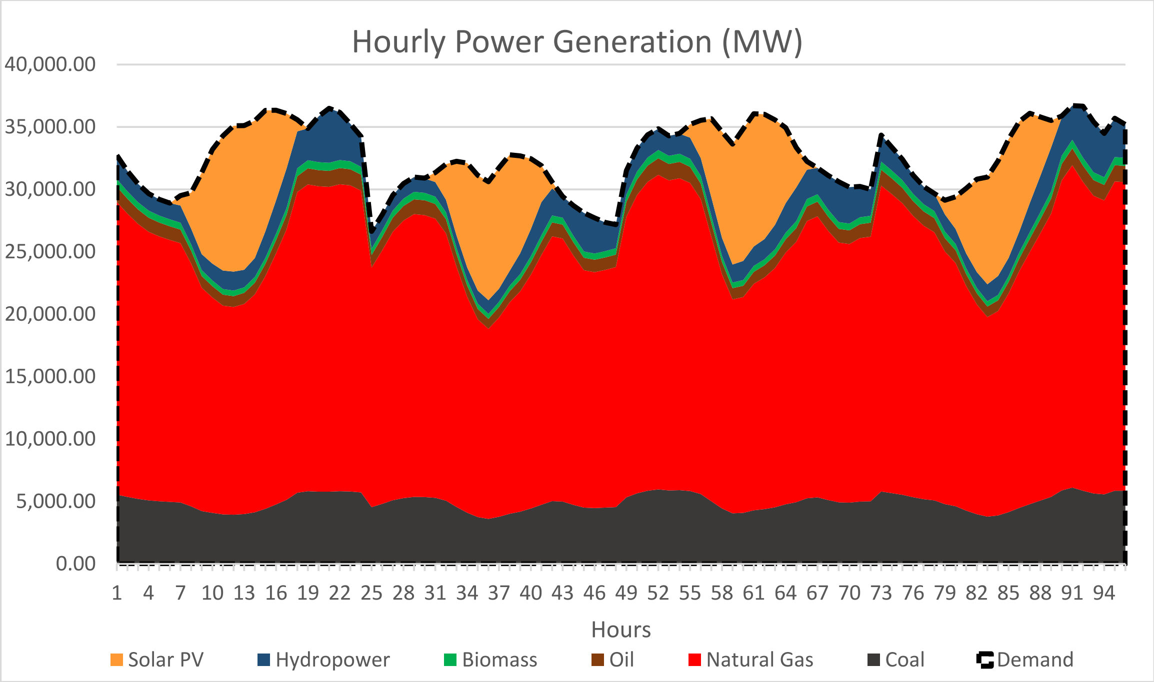

Fig. 13. Hourly Power Generation in Model 4.

Economic analysis

The calculated total cost was based on the net present value of the total cost over the energy system transition period (2020 to 2050). The two scenarios (long-term) analysed in this case were: 1) the Ref 2020 model towards the NETR 2050 model and 2) the Ref 2020 model towards the NETR 2050 OPT model. These calculated costs included the capital costs, O&M costs, and fuel costs. Based on the economic input data, the following results were obtained for the two scenarios: 1) For the NETR 2050, the total net present value was calculated to be 1210.7 billion USD, 2) With the LEAP-NEMO optimisation, the total net present value resulted in 1005.7 billion USD which resulted in approximately 205 billion USD cost savings over the transition period. Figs. 18 and 19 illustrate the main production costs for the two scenarios as extracted from LEAP through 5-year interval periods.

By comparing the two scenarios, the major contributor to the savings in the total net present value resulted from the fuel costs. These costs were reduced due to a smaller fraction of fossil fuel utilisation in the

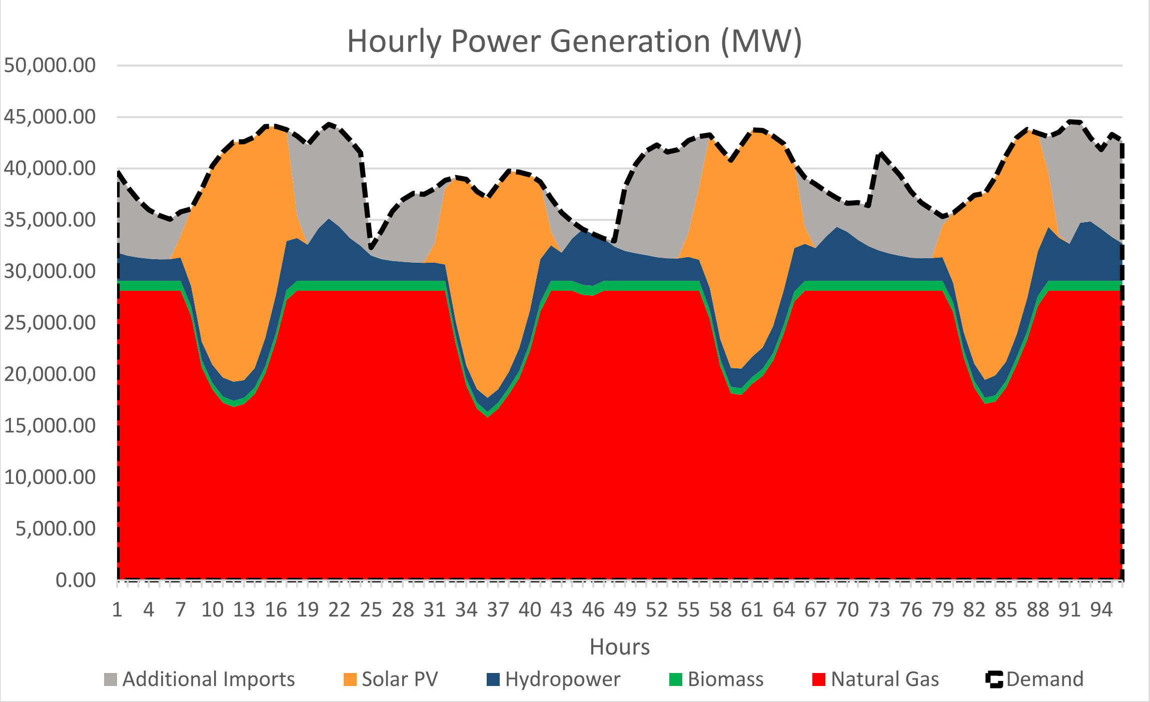

Fig. 14. Hourly Power Generation in Model 5 (NETR 2050).

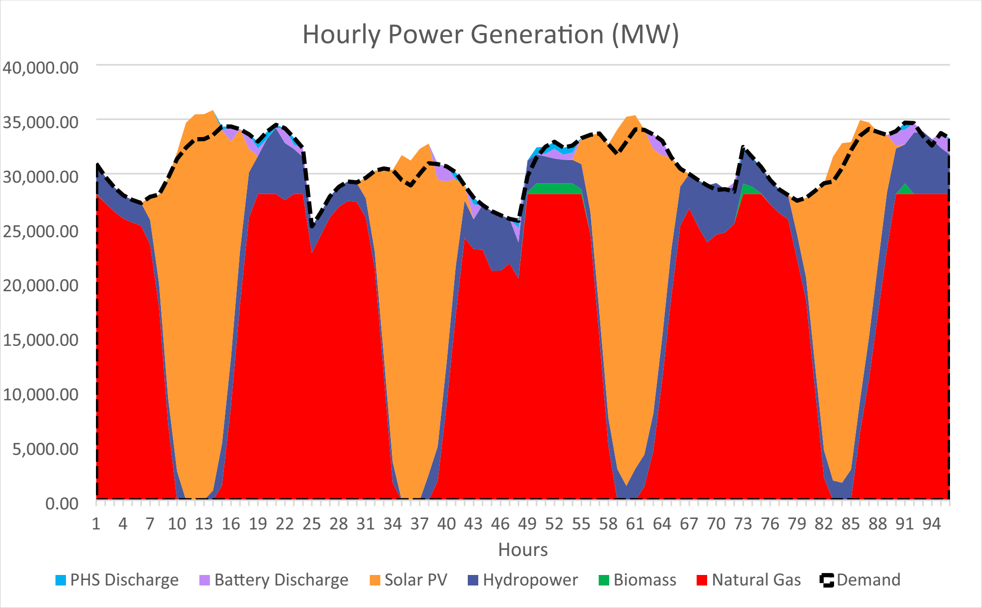

Fig. 15. Hourly Power Supply and Demand in Model 5 (NETR 2050 OPT).

electricity mix as compared to renewables, with the aid of energy efficiency for demand reduction. This enabled a quicker phasing out of coal power plants with smaller fractions of natural gas being used for electricity generation. As a result, higher RE generation fraction was attained for each year throughout the transition period. This economic analysis conducted is subject to uncertainty in key areas such as future fuel prices, capital costs, O&M costs, and electricity demand projections.

Sensitivity analysis

Even though the annual demand projections exhibited a growth from 2020 to 2050, each target year was modelled to have the same demand distribution pattern throughout the year with respect to its projected annual demand. To address this limitation, a sensitivity analysis was conducted on the NETR 2050 OPT model to understand how different electricity demand patterns would affect the electricity balance, ESS requirements, and emissions. The selected variations in design parameters were 1) the typical demand distribution pattern of Malaysia in 2020, 2) high peak demand distribution (10 % increase during peak demand hours), and 3) flattened demand distribution (10 % decrease during peak demand hours). After running LEAP-NEMO, the following results were obtained as illustrated in Fig. 20 and Fig. 21.

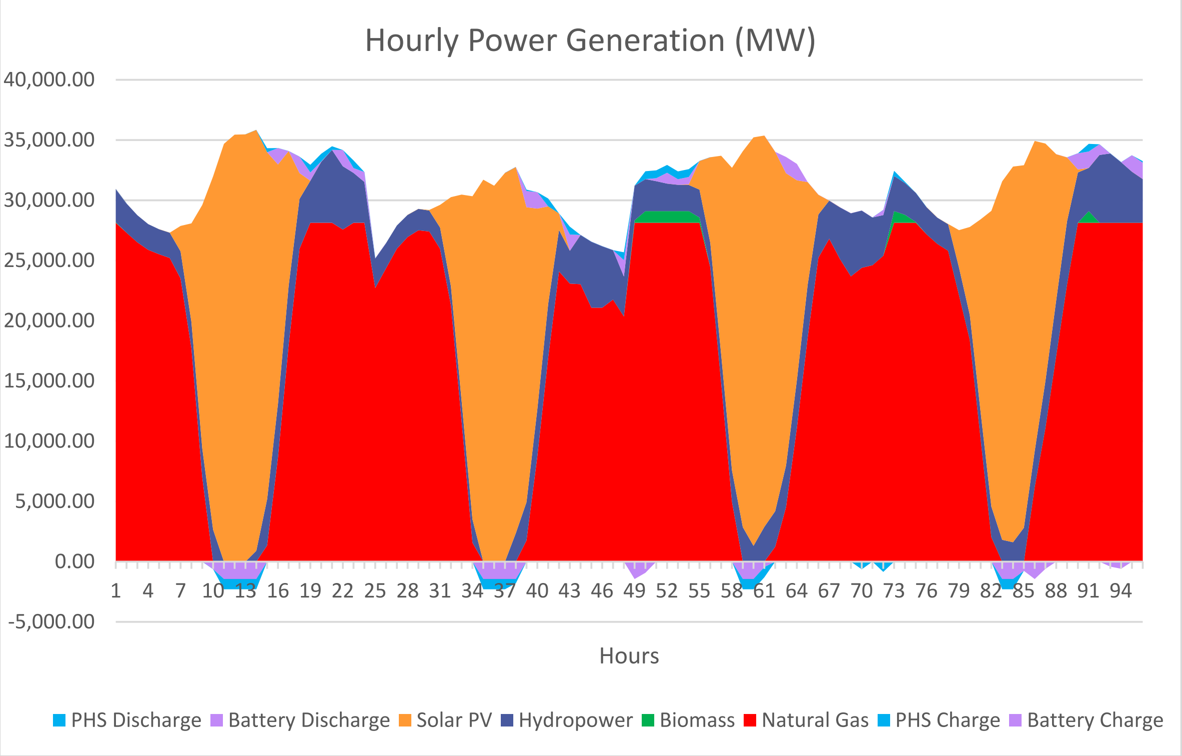

Fig. 16. Hourly Power Supply, Storage Charging, and Storage Discharging in Model 5 (NETR 2050 OPT).

Table 4
Technological Specifications of the Optimal ESS Sizing.

Storage Type	Peak Charging (MW)	Peak Discharging (MW)	Efficiency (%)	Full Load Hours (h)	Hourly Storage Carryover	Seasonal Storage Carryover
Li-ion BESS	1443.8	1357.2	94	6	Yes	No
PHS	849.2	645.4	76	24	Yes	Yes

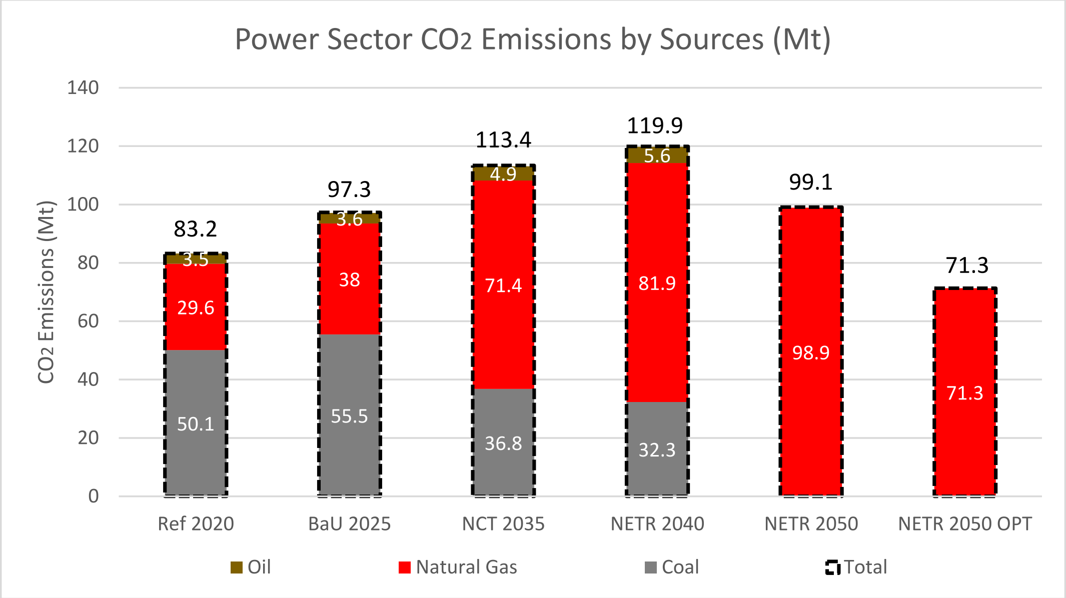

Fig. 17. Power Sector-based GHG Emissions by sources.

With the annual demand of 270.2 TWh/year for the NETR 2050 OPT model, the total electricity generated by all three variations exceed the demand. The high peak demand distribution has the highest excess in electricity generated, followed by the typical and flattened demand patterns. As there are larger mismatches in electricity supply and demand, there is higher electricity charged and discharged by the BESS

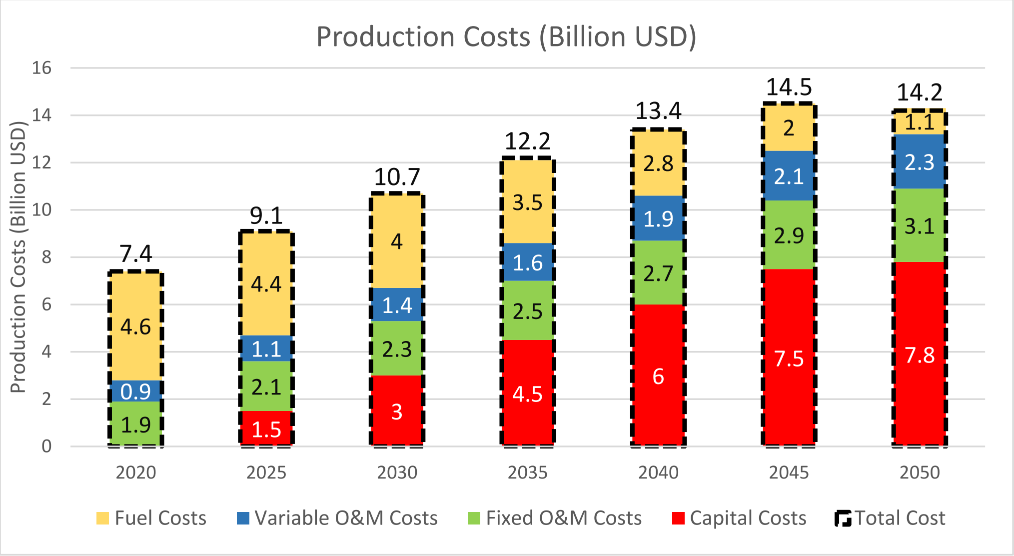

Fig. 18. Cost Production Parameters for Ref 2020 to NETR 2050 Scenario.

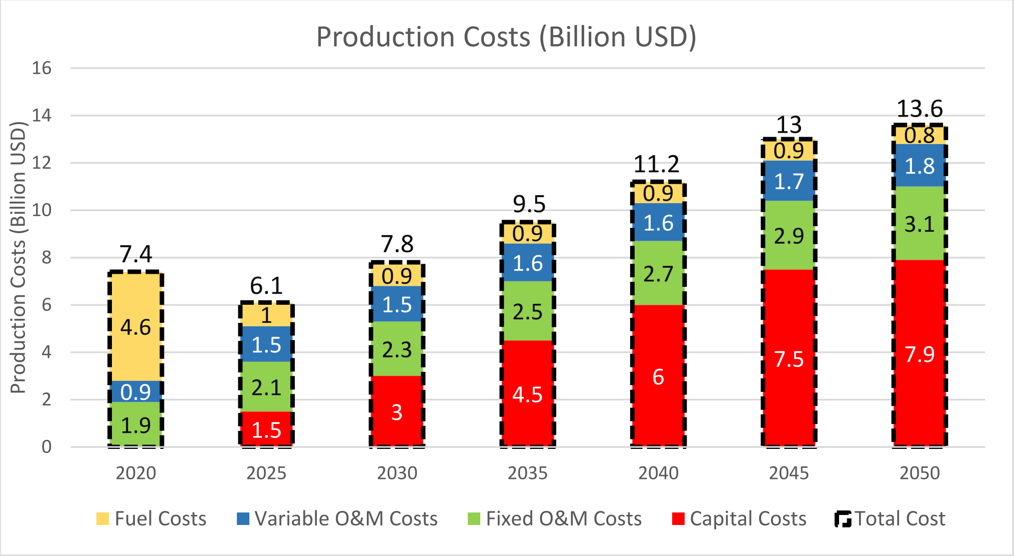

Fig. 19. Cost Production Parameters for Ref 2020 to NETR 2050 OPT Scenario.

and PHS. As the high peak demand gradually flattens, the hourly charging and discharging of ESS begin to decrease due to smaller mismatches in supply and demand. The flattened demand variation did not require the use of PHS, as the smaller capacity of BESS was enough to balance the mismatches. Additionally, there was a slight increase in annual natural gas generation moving from the high peak demand to flattened demand, followed by a slight decrease in solar and hydro generation in accordance to the dispatch rules of power plants. This resulted in the lowest power sector-based CO2 emissions (70.5 Mt) in the high peak demand variation, followed by a gradual increase towards the typical (71.3 Mt) and flattened demand (72.2 Mt) variations. By testing the LEAP-NEMO optimised model, this sensitivity analysis demonstrated that the ESS capacities were more sensitive to different demand distributions patterns compared to the electricity generated by power sources. Based on these findings, more ESS can enable higher VRE generation fractions in the power mix even during high peak demand distributions which will result in smaller power-sector based CO2 emissions.

Discussion

Recent work on the projection of electricity balance and emissions for Malaysia towards 2050 have been carried out in (Haiges et al., 2019) using TIMES and in (Handayani et al., 2022) using LEAP-NEMO. Haiges et al. (Haiges et al., 2019) investigated three scenarios namely, the BaU, nuclear, and high RE with PHS. A low carbon power sector pathway with a 98.37 % RE generation fraction by 2050 through 6 RE technologies and PHS was proposed. Handayani et al. (Handayani et al., 2022) investigated reference, RE policy, and net-zero emissions pathways towards 2050 for ASEAN nations, including Malaysia. For the net-zero scenario, this study indicated that the ASEAN countries need to capitalise on their underutilised RE potential, mainly driven by solar PV. It was also found that the deployment of ESS becomes a need to balance high VRE penetration. Building on previous studies, this paper contributes to the literature on energy transition pathways for Malaysia through the application of LEAP-NEMO optimisation to determine the total optimal ESS capacities required by Malaysia’s power sector by 2050. In terms of total energy generation results throughout 2050, BESS

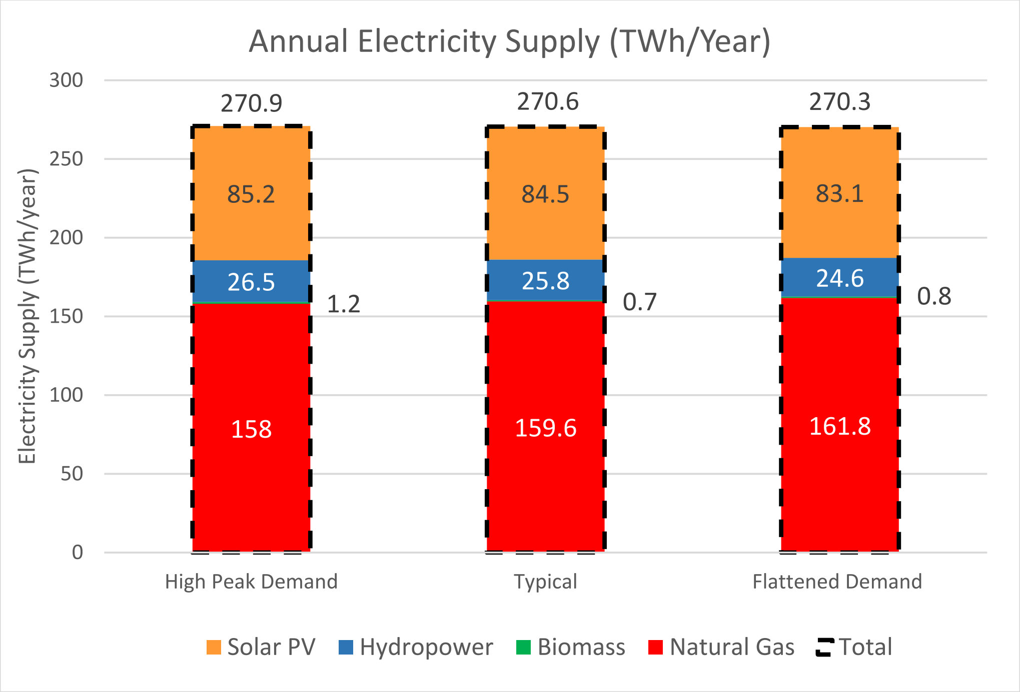

Fig. 20. Sensitivity Analysis Results of Annual Electricity Supply.

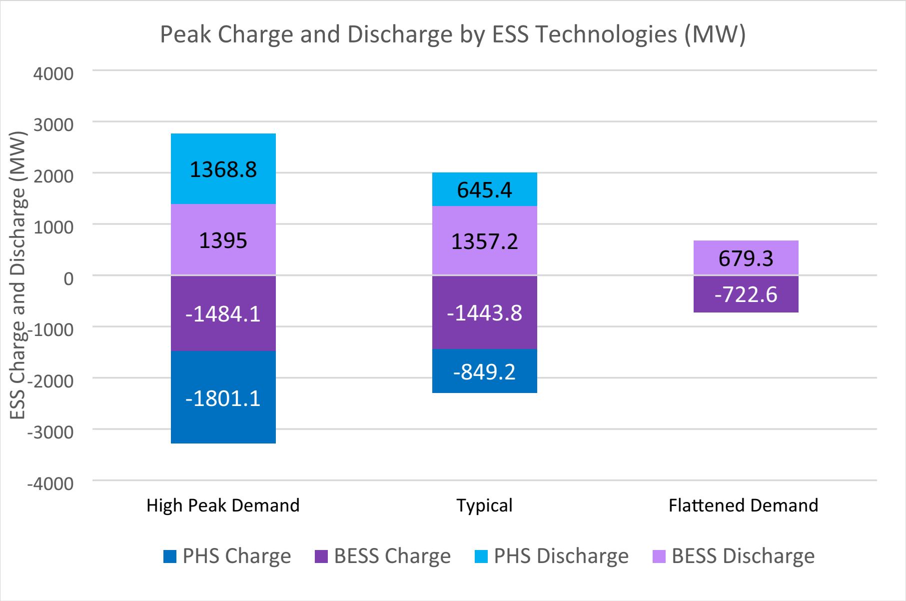

Fig. 21. Sensitivity Analysis Results of Peak Charge and Discharge by ESS Technologies.

and PHS resulted in −134.6 GWh and − 263.2 GWh respectively.

Among the RE sources, solar PV plays a substantial role in Malaysia's power sector towards the future, due to its high potential. ESS technologies are mainly integrated to balance VRE to avoid mismatches in electricity supply and demand (Fernandez et al., 2024a). Due to the limited potential of PHS, BESS is anticipated to play an important role. Despite significant cost reductions in recent years, li-ion batteries remain costly. Additionally, this BESS technology is not suitable for long-term storage, as the stored charge dissipates over time (DGE MEMR, 2021). Therefore, the advancement of technological learning curves in BESS and the exploration of PHS potential are crucial for attaining a successful long-term energy transition towards net-zero in Malaysia's power sector. The country could also drive research and development of ESS technology to address key areas such as techno-economic analysis, system sizing, demand response, and operational control (Chatzigeorgiou et al., 2024). However, there are challenges to implement BESS in Malaysia such as high investment costs, grid compatibility, clear guidelines from grid operators, optimal control of BESS operation under uncertain conditions, and land acquisition for BESS plants (Mohd Razif et al., 2024).

Projected increase in power trade among ASEAN nations with the aid of CCUS towards attaining net-zero emissions were studied (Zhong et al., 2025). The advantages of cross border interconnection for power trading are that the high RE potential in the countries can help lower emission intensity in the regional power sector. Moreover, it would enable net savings by reducing the need for investment in generation and storage technologies. Finally, this interconnection will enhance system reliability by decreasing internal congestion in the ASEAN countries, allowing for the use of neighbouring countries' transmission networks to support cross-border electricity trade (Ahmed et al., 2017). Exploring the RE transition in the ASEAN power sector, particularly focusing on cross-border grid interconnections between Malaysia and its neighbouring ASEAN countries, presents a promising area for future research. This could alter the optimal capacity requirements for ESS technologies, as further investigation into the optimal techno-economic-environmental balance of RE, ESS and cross-border grid interconnections across the ASEAN network is conducted.

The following policy recommendations are proposed based on the findings of this paper with review of recent literature on Malaysia's energy transition (Fernandez et al., 2024b; Majekodunmi et al., 2023). With the projected increase in LSS capacities towards 2050, implementing techno-economic-environmental optimisation strategies for LSS installations will play a key role in reducing land use (Al-Khayat et al., 2025; Thadani & Go, 2023). Installation of building-integrated and floating PV can contribute to increasing RE generation at distributed industrial, residential, and commercial levels thereby, reducing grid dependency (Teoh et al., 2020; Thoy & Go, 2022). The formulation of a robust value chain for BESS across ASEAN countries is crucial to enhancing regional energy security and enabling more effective VRE integration, ensuring reliability in the power supply (Moa & Go, 2023; Yoo & Ha, 2024). Considering the essential role of ESS in enabling high VRE generation, ASEAN can advance the implementation of ESS solutions to capitalise on technological advancements. A gradual phasing out of subsidies for fossil fuel power plants is essential to promote cleaner energy alternatives and help meet climate goals by reducing dependence on sources with high emission factors. Additionally, improving the efficiency of biomass sourcing and utilisation, establishing centralised collection hubs could streamline logistics, providing a more consistent and cost-effective biomass supply for energy production, thus enhancing overall sector performance, and reducing operational inefficiencies (Ozturk et al., 2017). This can improve the RE fraction of the electricity generation mix by utilising biomass potential in Malaysia. Modernising transmission and distribution networks, incorporating advanced power flow control technologies, upgrading existing power plants, and implementing smart grid technologies would improve energy distribution, reduce losses, and ensure optimal integration of VRE sources into the grid (Abuelrub et al., 2019; AbuElrub et al., 2020; Fernandez & Go, 2023a; Fernandez & Go, 2023b; Hassan et al., 2024; Lin et al., 2023). Expanding the use of CCUS technologies is a necessary strategy to offset CO2 emissions from existing fossil fuel power plants, thereby supporting decarbonisation efforts (Nasir & Go, 2024). Also, providing incentives to industries making notable strides in green technology advancement would stimulate innovation and accelerate the adoption of environmentally friendly technologies, contributing to a sustainable industrial transformation (Wang et al., 2024). Furthermore, promoting investment in hydrogen technologies, including the development of production and distribution infrastructure as well as its use in applications like transportation fuels, could foster a clean, scalable energy solution that supports long-term energy security and decarbonisation efforts across multiple sectors (Alias & Go, 2023; Zakaria et al., 2023). Research on models incorporating the optimal configuration of utility grids, with multi-point connections to the national grid, can enable more accurate projections of the nation's future electricity balance (Al-Masri et al., 2019).

Conclusion

Attaining global net zero emissions demand the involvement of all nations, both developed and developing. Given that the energy sector is the largest source of CO2 emissions worldwide, it is crucial for the global power industry to undergo decarbonisation. Five Malaysian national energy system models were developed in LEAP from 2020 to 2050 based on the energy transition roadmaps and high temporal resolution electricity data from the Malaysian GSO via real-time IEA. The findings from this research projects how the Malaysian power sector would operate in the future with the gradual phasing out of coal power plants, the scaling up of solar PV and natural gas, the projected rise in electricity demands, electricity imports and ESS for hourly demand matching, and energy efficiency for demand reduction. These analyses were followed up by the optimal integration of BESS and PHS using LEAP-NEMO framework. In Model 1, the total electricity generation was at 153.8 TWh/year which are generated by coal (43.76 %), natural gas (43.04 %), hydro (6.11 %), oil (3.9 %), biomass (2.34 %), and solar (0.91 %). In Model 5, this value was projected to be at 347 TWh/year with contributions mainly from natural gas (63.78 %), followed by solar (17.4 %), additional imports (9.33 %), hydro (7.3 %), and biomass (2.2 %). With LEAP-NEMO optimisation and energy efficiency, Model 5 was improved to eliminate the dependency on additional imports required to match the demand. This resulted in a total annual electricity generation of 270.6 TWh/year with contributions from natural gas (58.98 %), solar PV (31.23 %), hydropower (9.53 %), and biomass (0.26 %). Based on the hourly results of balancing supply and demand throughout the year, the optimum ESS resulted in BESS with peak charging/discharging of 1443.8/1357.2 MW and 6 full load hours, and PHS with peak charging/discharging of 849.2/645.4 MW and 24 full load hours. In terms of total energy generation results throughout the year, BESS and PHS resulted in −134.6 GWh and − 263.2 GWh respectively. The total power sector-based GHG emissions from Model 1 was 83.2 Mt. CO2 driven by coal (60.2 %), natural gas (35.6 %), oil (4.2 %), and biomass (0.1 %). Model 5 projected 99.1 Mt. CO2 mainly driven by natural gas (99.8 %), followed by biomass (0.2 %) and this improved to 71.3 Mt. CO2, fully driven by natural gas (100 %) after optimisation. For the total emissions in all sectors, the results for models 1 to 5 resulted in 287.5, 321.5, 382.1, 404.5, and 466.3 Mt. CO2 respectively. After optimisation, model 5 was improved to be at 449.7 Mt. CO2 mainly due to the lower generation of natural gas in the power sector. In summary, the findings from this paper indicated that Malaysia's power sector will need substantial adoption of ESS and EE to accommodate for the electricity imbalances that are estimated to occur towards 2050. The limitations in this study were that the high temporal resolution data of electricity demand for the reference year were linearly upscaled based on the specified CAGR for future years. Future work can be carried out in investigating: 1) Techno-economic-environmental optimisation of future electricity balance with optimum proportion of electricity supply, demand, storage charge, storage discharge, with import and export among neighbouring ASEAN countries, 2) biomass potential of Malaysia to increase RE generation fraction to reduce dependency on imports, 3) modelling of electric vehicles (EV) in Malaysia and the environmental impacts of the transport sector. This would enhance the reliability of the findings and provide valuable insights in the uncertainties related to future energy system models in Malaysia and other developing countries.

CRediT authorship contribution statement

Malcolm Isaac Fernandez: Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Yun Ii Go:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Wolf-Gerrit Früh:** Supervision. **Dennis M.L. Wong:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by Heriot-Watt University Malaysia through the James Watt Scholarship.

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